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Lifetime of Polyimide under Repetitive Impulse Voltages

Yan Yang and Guangning Wu

Abstract

Polyimide (PI) is a commonly used insulating material to resist surface discharge, for instance, as turn-to-turn insulating material in inverter-fed motors driven by pulse width modulation (PWM) converters. Under the effect of repetitive impulse voltages, PI is expected to withstand surface partial discharge (PD) during service. However, lifetime under repetitive impulse voltages is much shorter than that under AC voltages due to storage effect of charges. Many approaches have been proposed to improve lifetime of polyimide under repetitive impulse voltages, such as using nanocomposites, surface modification, and structure design. In this chapter, we will discuss the lifetime of polyimide under repetitive impulse voltages and corresponding theoretical mechanism, together with modification approaches and their effects on lifetime improvement.

Keywords: lifetime, repetitive impulse voltages, surface discharge, nanocomposites, surface modification

1. Introduction

Polyimide (PI) is used as insulating material for resist surface discharge because of its excellent electrical, thermal, and mechanical characteristics [1, 2]. PI films are usually expected to withstand surface discharge caused by repetitive impulse voltages. For example, surface partial discharge occurs during lifetime of turn-to-turn insulation of inverter-fed traction motors due to the driven pulse width modulation (PWM) converters, which has become one of the most important factors for surface degradation and final premature failures of the insulation of inverter-fed traction motors. Therefore, the PD-dependent lifetime of PI films under repetitive impulse voltages needs to be improved to meet the requirement for rapid development of industry applications [3, 4].

To provide a comprehensive understanding to lifetime of PI under repetitive impulse voltages and to clarify the emerging problems, we review the recent progress in partial discharge characteristics, degradation, and charge storage effect under repetitive impulse voltages. Particular attention is paid on lifetime improvement approaches, such as using nanocomposites and surface modification.

2. Lifetime of polyimide under repetitive impulse voltages

2.1 Lifetime and partial discharge characteristics of polyimide under repetitive impulse voltages

Figure 1 shows the system for testing lifetime and partial discharge characteristics of polyimide under repetitive impulse voltages. Bipolar continuous square impulse voltage was conducted. The amplitude, risetime, duty cycle, and frequency of applied voltage were 1 kV, 40 ns, 50%, and 10 kHz, respectively. The electrodes used in the test were designed according to the standard of ASTM 2275 01, including a rod electrode, a plate electrode, and an insulating board [5]. By this configuration, we can obtain the voltage endurance of solid electrical insulating materials subjected to surface partial discharges. The PD signal was measured by an UHF antenna.

Figure 2 shows the lifetime of PI under repetitive impulse voltages, which decreases sharply with increasing temperature. The lifetime values are much shorter than that under AC voltages [6].

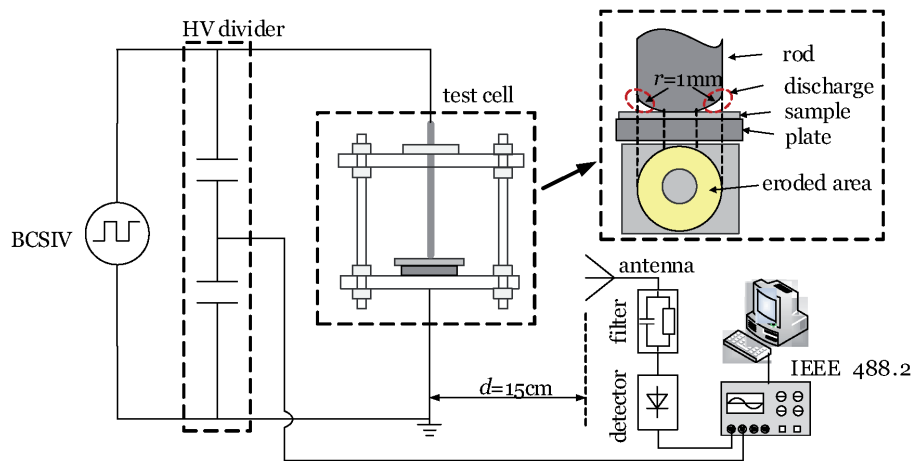


Figure 1.
Schematic diagram of the PD aging test system.

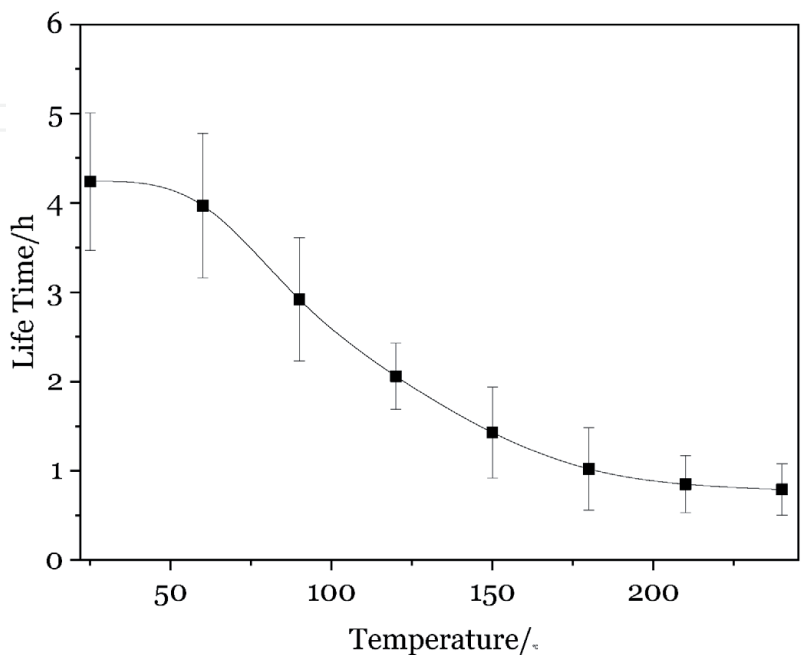
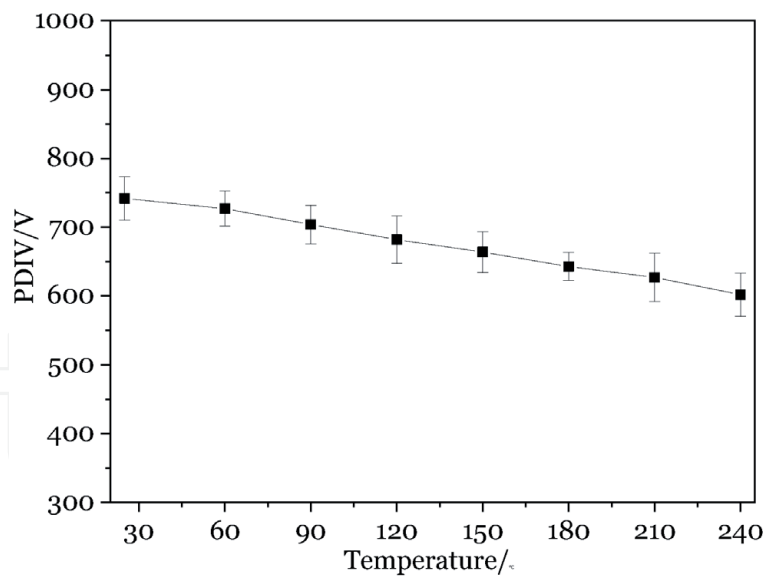
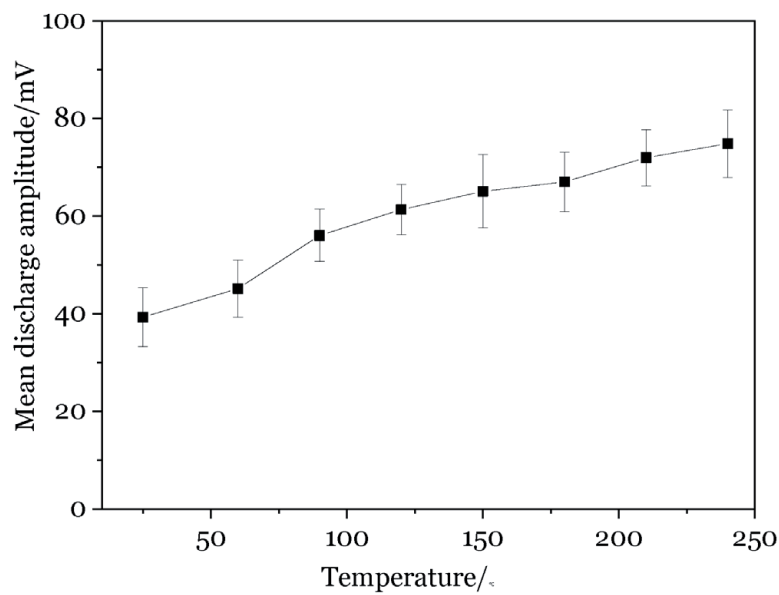


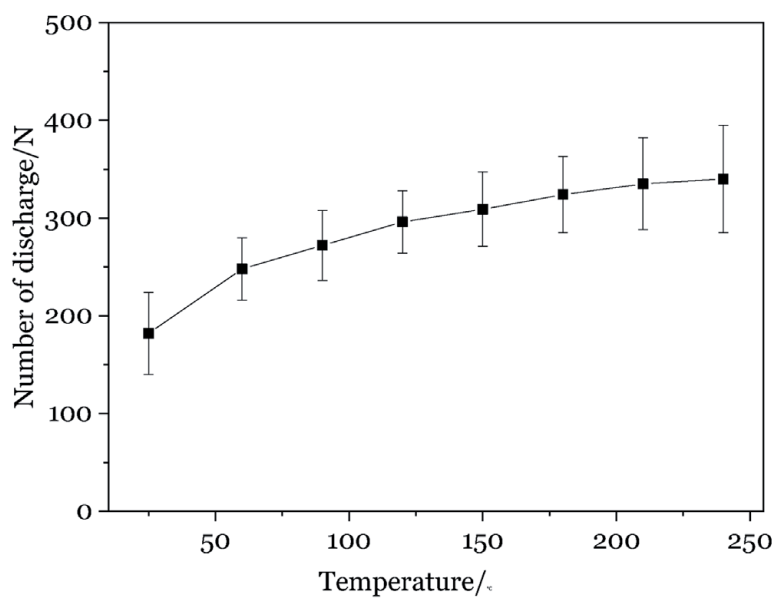
Figure 2.
Lifetime of PI under repetitive impulse voltages [6].



(a)



(b)



(c)

Figure 3.
PD characteristics of PI films with increasing temperature. (a) PDIV, (b) PD amplitude, (c) PD number.

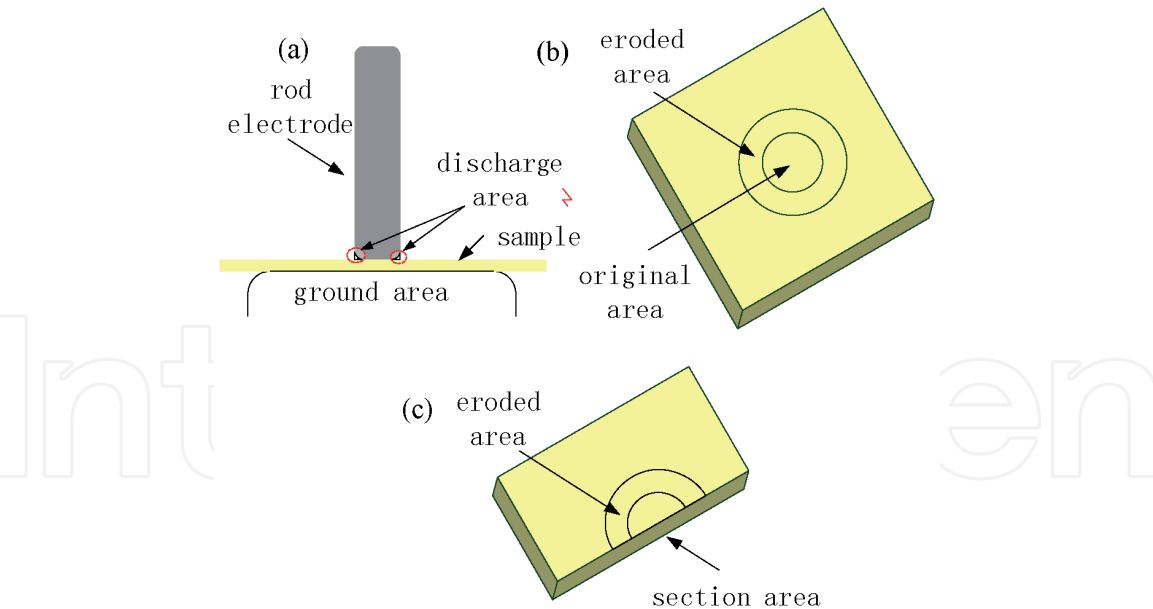


Figure 4.
Sample discharge area and eroded area of sample [6].

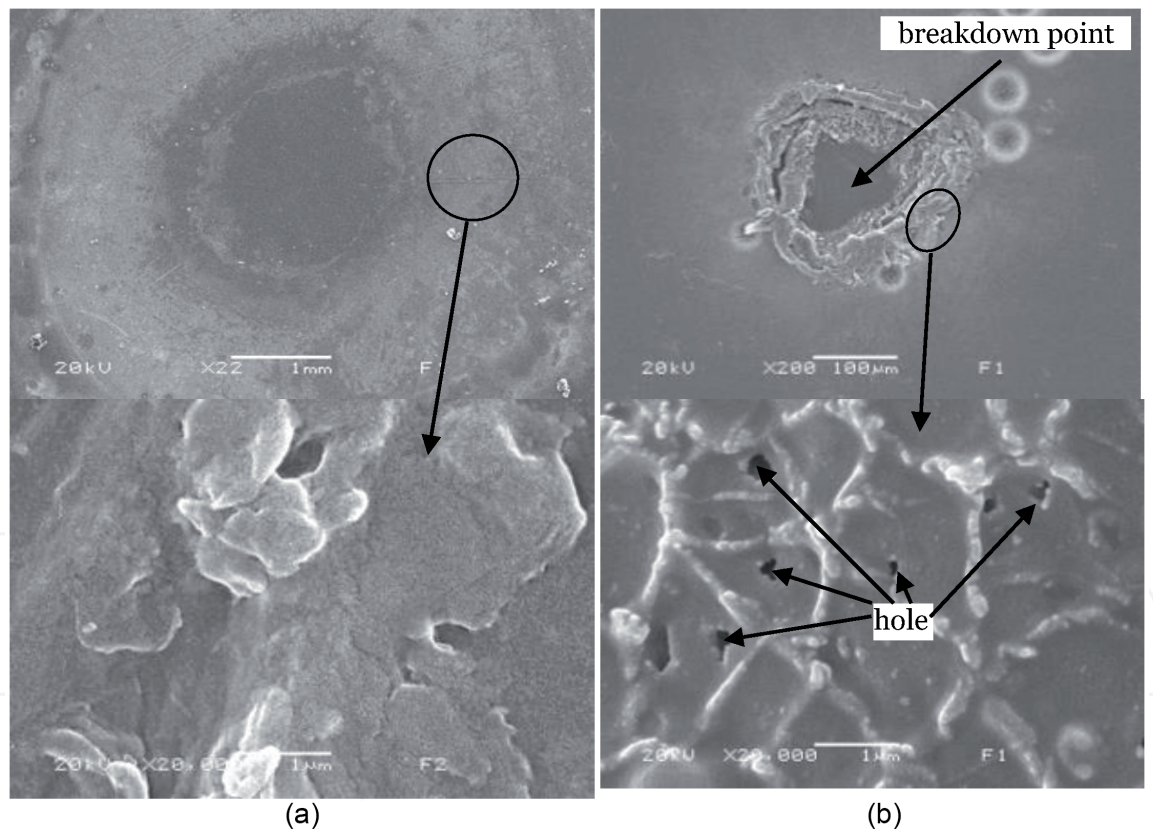


Figure 5.
Microtopography of PI films after 3-h aging and breakdown. (a) 3-h aging and (b) breakdown.

Figure 3 shows the PD characteristics, including the PDIV, PD amplitude, and PD number, of PI films under repetitive impulse voltages as a function of temperature. PDIV decreases with increasing temperature; on the contrary, PD amplitude and PD number increase with increasing temperature. All these parameters are higher than that under AC voltages [6].

2.2 Partial discharge-induced degradation under repetitive impulse voltages

Due to the electrode structure as shown in **Figure 2**, surface discharge would occur in the air gap between the sample and the upper rod electrode during lifetime testing. Certain region on the film surface, as shown in **Figure 4**, would be corroded by surface discharge generating high-energy electrons, ultraviolet rays, and high-activity chemical groups [7, 8]. The microtopography of PI films after 3-h aging and breakdown (lifetime: 6 h and 10 min) under repetitive impulse voltages is shown in **Figure 5**. An obvious circle can be seen on the surface of aged PI film, which is eroded as the consequence of surface discharge, resulting in surface roughness and morphology changing. From the microscopic view of the breakdown point as shown in **Figure 5(b)**, the mesh structure and voids can be observed on the surface microtopography around the breakdown point obviously, indicating degradation of PI occurred during discharge.

2.3 Storage effect of charges under repetitive impulse voltages

Under repetitive impulse voltages, partial discharge-induced degradation would be intensified because of charge storage effect. We discuss the electrical field distribution on discharge region of the sample surface, as shown in **Figure 6**, where E_i is the electric field in the air gap between the sample and the edge of the upper electrode. When external electric field reverses, accumulated charges on the film surface will enhance the electric field in the air gap between the rod and the sample, as shown in **Figure 6**. Assuming the external electric field is negative, the charge-induced electric field in the air gap E_q is proportional to the difference between the charges on the rod electrode Q_{up} and that on the film surface Q_{down} , namely, $E_q \propto (Q_{up} - Q_{down})$. Thus, the effective electric field in the air gap can be obtained, $E_i = E_t + E_q$, where E_t is the external electric field. Since the charges on the film surface are unable to dissipate in such short rising time, the Q_{down} can be considered as a constant. When the external electric field reverses and becomes

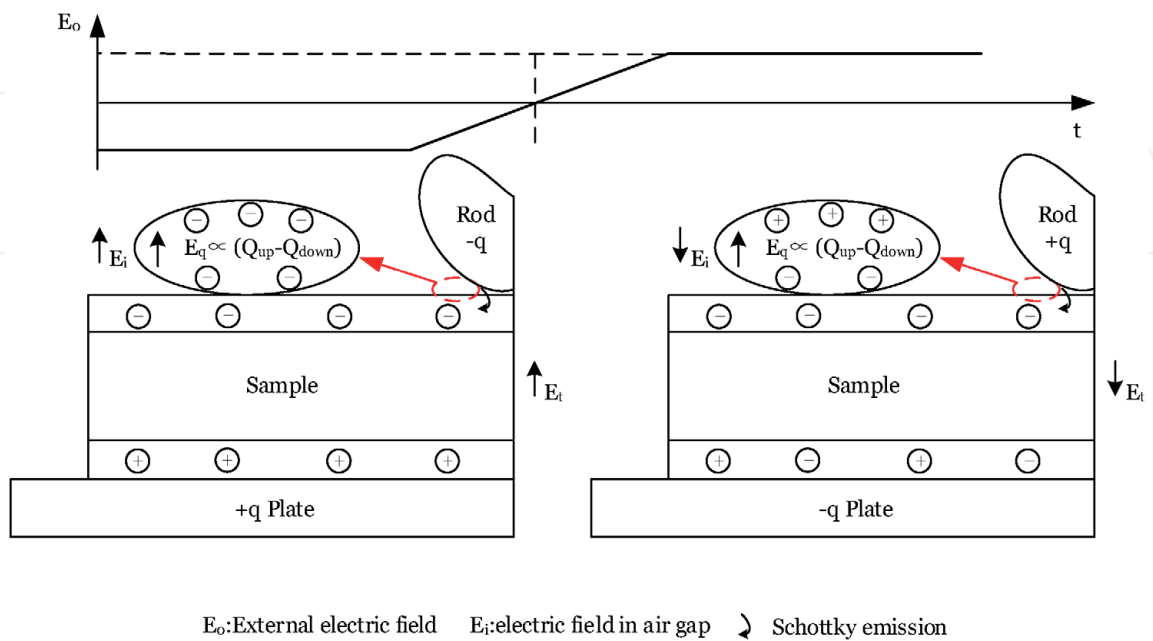


Figure 6.
The electric field change in air gap when external electric field inverses from negative to positive side [9].

positive, the E_q is proportional to the sum of the charges on the rod electrode Q_{up} and that on the film surface Q_{down} , namely, $E_q (Q_{up} + Q_{down})$. As the charge continues accumulating, the value of E_i can increase to a critical value, and then PD would take place.

3. Approaches for lifetime improvement

3.1 Polyimide nanocomposites

PD characteristics and lifetime repetitive impulse voltages would be improved by using polyimide nanocomposites. **Figure 7(a)** shows the PDIV of PI and PI/ Al_2O_3 nanocomposites. PDIV increases with increasing nano-alumina content. The PDIV of PI/ Al_2O_3 (8 wt.%) increases from 693 to 782 V (12.8% increase) compared with that of PI. This means the discharge threshold is much higher for PI/ Al_2O_3 nanocomposites. **Figure 7(b)** gives the PD amplitude and number recorded in 1 min, which both decrease with increasing nano-alumina content, revealing that the decrease in PD intensity is attributed to the effect of nano-alumina.

As shown in **Figure 8**, the PD resistance is enhanced significantly as the content of nano-alumina increases. The lifetime values of PI/ Al_2O_3 with nano-alumina content of 0, 2, 5, and 8 wt.% are 37.8, 52.1, and 61.9 min, increasing by 92.8, 165.8, and 215.8% respectively, compared with that of PI. This demonstrates that the nano-alumina helps to prolong the lifetime of PI.

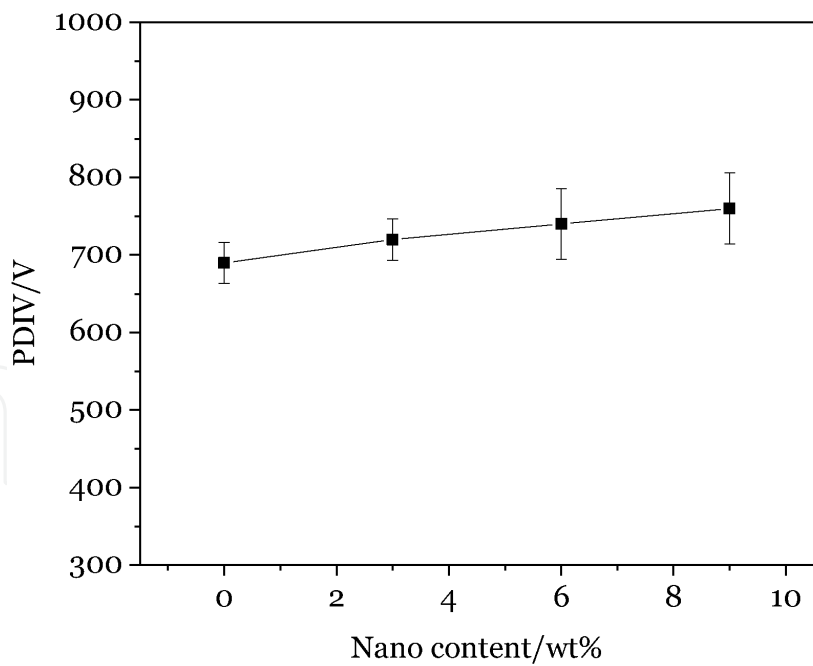
In polyimide nanocomposites, the melting point of nano-alumina particles is higher than that of polyimide. Under the effect of surface discharge, nanoparticles float on the film surface, forming a protective layer to prevent the polyimide matrix from further erosion. This layer, therefore, is able to mitigate the PD effects on films and block the erosion path, which can help avoid the same local point being eroded continuously. In contrast, without nanoparticles, the erosion will follow a specific path and lead to breakdown much faster. This is why there are a number of micro-cavity groups in PI/ Al_2O_3 nanocomposites but only a few big cavities in the PI films, as shown in **Figure 6 c** and **d**. Thus, the incorporation of nanoparticles improves the physical characteristics of PI/ Al_2O_3 nanocomposites, because nanoparticles can act as obstacles in the erosion path, and then the degradation of polymer can be reduced, and prolonged lifetime of PI/ Al_2O_3 nanocomposites can be obtained subsequently.

In addition, some acid compounds (e.g., the amic acid and the nitric acid) are generated during PD aging. Meanwhile, new bonds in PI/ Al_2O_3 nanocomposites are the weakest, subsequently the ether linkage, imide ring, and then aromatic ring. Those weakest bonds in interfacial regions would be destroyed at the first stage of aging, so the dissociations of polyimide molecules would be reduced. Because of the chemical bonding between nanoparticles and PI molecules, the degradation of polymer can be reduced, and prolonged lifetime of PI/ Al_2O_3 nanocomposites can be obtained consequently.

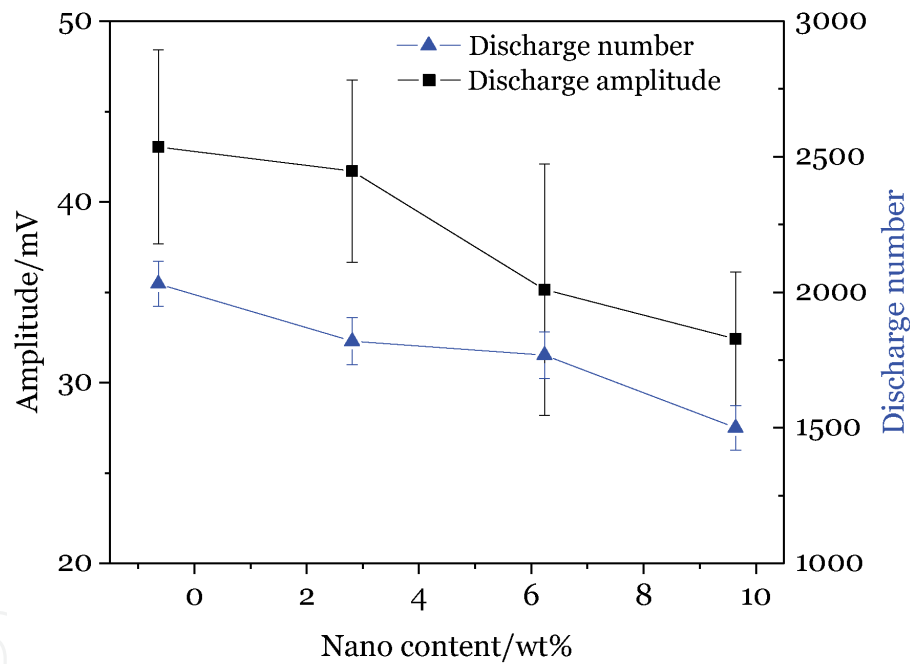
Moreover, higher surface conductivity facilitates surface charge dissipation and leads to low PD intensity. Lower trap density is responsible for the low possibility of charge recombination and the corresponding released energy. All these factors improve the electrical characteristics of PI/ Al_2O_3 nanocomposites resulting in reduced degradation of polymer and longer lifetime.

3.2 Surface modification

Lifetime of PI under repetitive impulse voltages would be further improved by surface modification. **Figure 9** shows the lifetime of PI and PI/ Al_2O_3



(a)



(b)

Figure 7.
PD characteristics of PI and PI/Al₂O₃ nanocomposites. (a) PDIV and (b) PD amplitude [9].

nanocomposites under repetitive impulse voltages, after being treated by nonthermal plasma in atmospheric air with different treating times. For both PI and PI/Al₂O₃ nanocomposites, lifetime can be prolonged by plasma treatment. Apparent improvement of lifetime can be seen in the first 20 s of treating time. However, the lifetime decreases with increasing treating time, when the treating time is longer than 20 s. When the treating time exceeds 30 s, the lifetime decreases sharply, by reaching the values even shorter than that of the untreated samples. For plasma-treated samples, with shallower trap energy level, less charge accumulation facilitates charge dissipation and local electric field mitigation, leading to suppressed PD intensity and longer lifetime. Active groups containing oxygen and nitrogen, which are introduced during plasma treatment, are responsible for trap energy

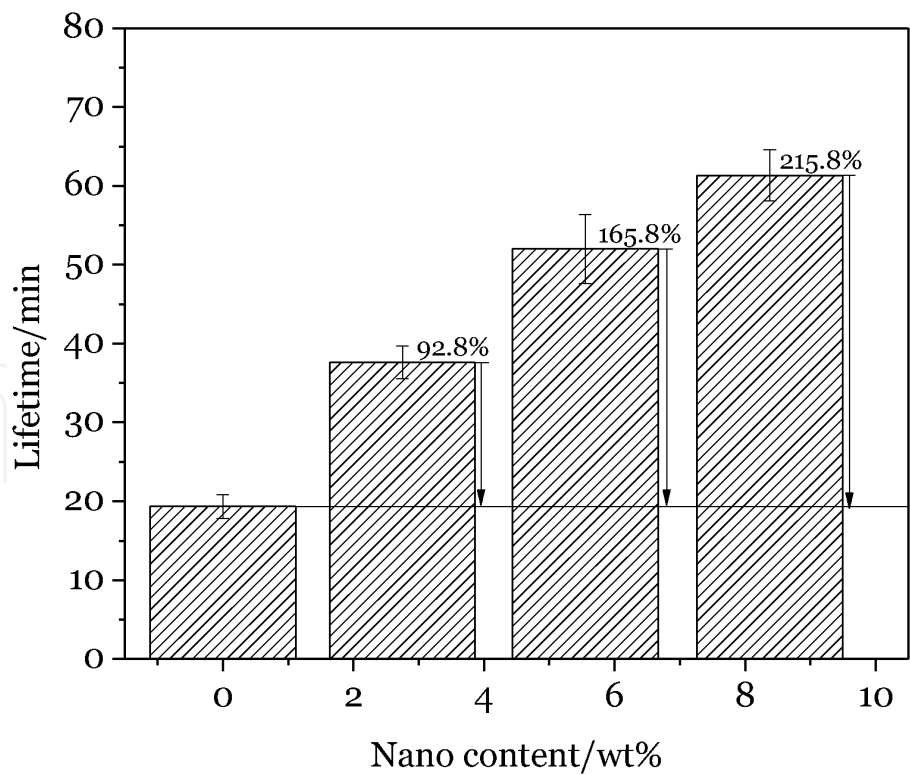


Figure 8.
Lifetime of PI and PI/Al₂O₃ nanocomposites under PD aging [9].

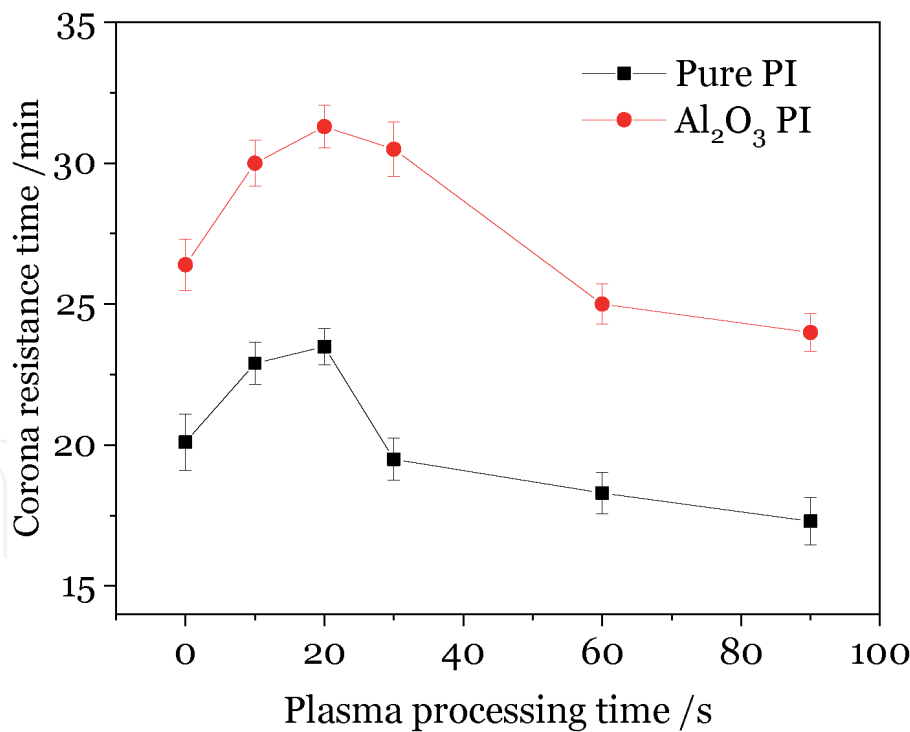


Figure 9.
Lifetime of PI and PI/Al₂O₃ nanocomposites with different plasma treating times under repetitive impulse voltage.

distribution modification of PI films. An appropriate treating time is the key factor to introduce reactive groups on film surface and prolong the lifetime.

3.3 Structure design

Structure design is another effective approach to improve lifetime of PI under repetitive impulse voltages. **Figure 10** shows the lifetime of PI, PI/Al₂O₃

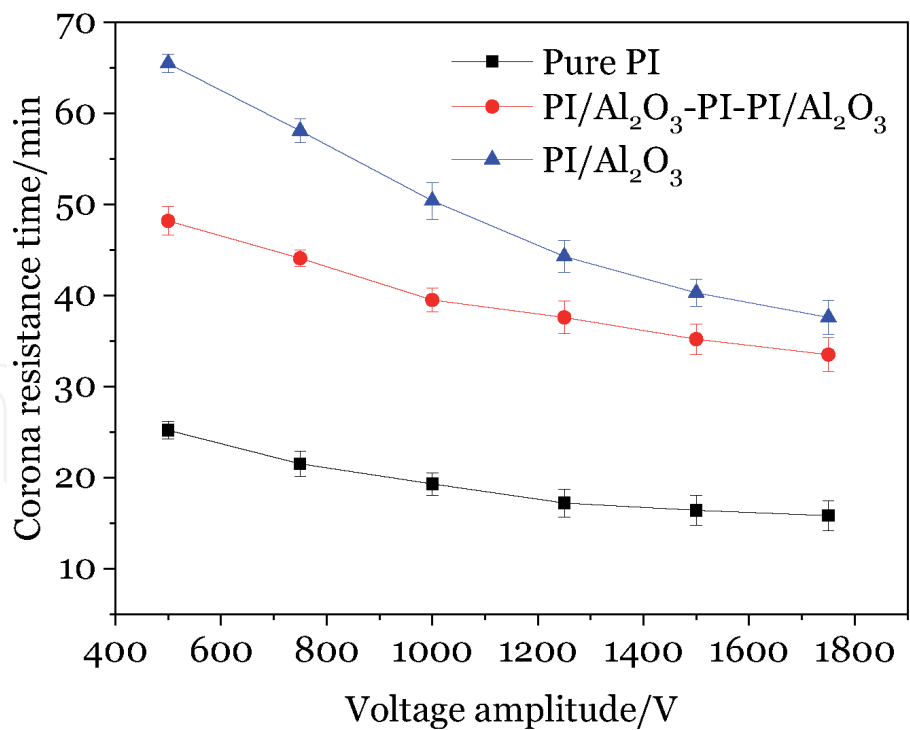


Figure 10.
Lifetime of PI, PI/Al₂O₃ nanocomposites, and PI/Al₂O₃-PI-PI/Al₂O₃ films under repetitive impulse voltages as a function of applied voltage (room temperature) [10].

nanocomposites, and PI/Al₂O₃-PI-PI/Al₂O₃ films under repetitive impulse voltages as a function of applied voltage. For all samples, lifetime decreases with increasing applied voltage. As the thickness of these three types of samples is all 60 mm, the lifetime of PI/Al₂O₃ nanocomposites are the longest. However, the results shown in **Figure 10** were tested at room temperature. Considering the effect of temperature, lifetime of PI/Al₂O₃-PI-PI/Al₂O₃ films is longest when the temperature is higher than 90°C, as shown in **Figure 11**. For applications such as inverter-fed motors, the

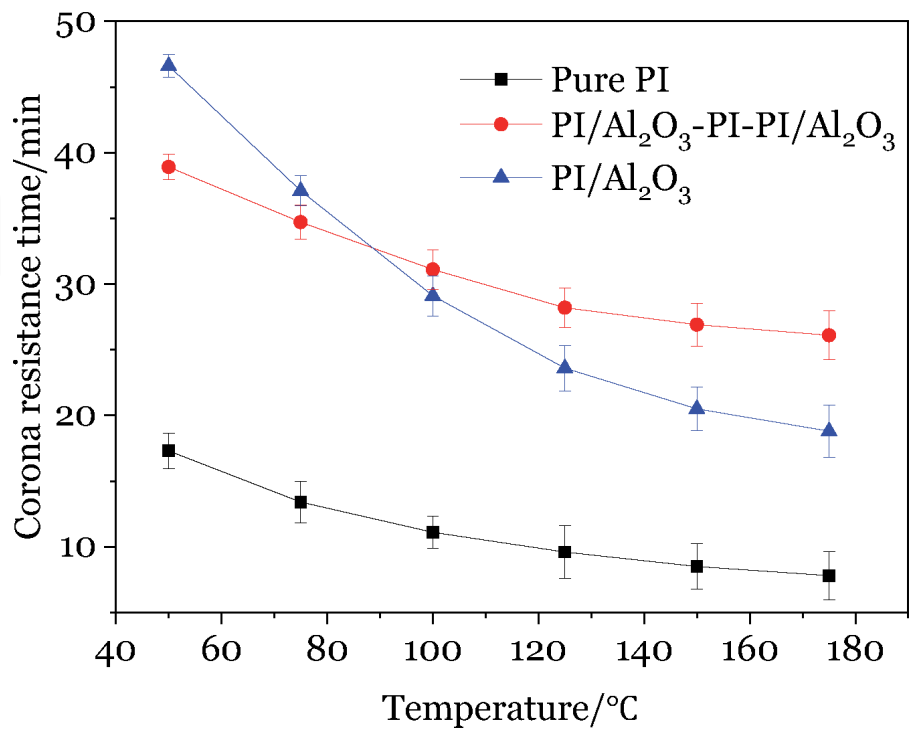


Figure 11.
Lifetime of PI, PI/Al₂O₃ nanocomposites, and PI/Al₂O₃-PI-PI/Al₂O₃ films under repetitive impulse voltages as a function of temperature (1 kV) [10].

operating temperature of PI is usually higher than 90°C; thus layered structure is an important approach to improve lifetime for industry applications.

4. Conclusion

PD-dependent lifetime of PI under repetitive impulse voltages is a key parameter for its industry applications. Due to charge storage effect under repetitive impulse voltages, partial discharge-induced degradation would be intensified, resulting in a shorter lifetime. By using nanocomposites, surface modification, and structure design, the lifetime would be prolonged.

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